# A Scaling Relation Between the Moment Release due to Aseismic Motion and the Injected Volume of Fluid

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**Abstract**

Constraining the moment release of injection-induced earthquakes is of paramount importance to reduce the seismic hazard in the geo-energy industry. Recent studies suggest that a significant part of the moment release during fluid injections can be due to aseismic motion, namely, *aseismic moment* M0. Current models of injection-induced aseismic moment do not incorporate fault rupture mechanics. Here, we present a theoretical and numerical analysis that highlights a possible scaling relation between the aseismic moment and a key operational parameter, the injected volume of fluid V. The scaling relation emerges from the model of a stable frictional shear crack that propagates in mixed mode (II+III) on a planar fault interface. The interface is characterized by a constant hydraulic transmissivity and a shear strength that is equal to the product of a constant friction coefficient and the local effective normal stress. Fluid is injected right into the fault interface at a constant flow rate. The resulting relation between the aseismic moment and the injected volume is M0=A[?] V^(3/2). The prefactor A accounts for the dependence of the aseismic moment on the pre-injection stress state, the parameters of the injection (notably, the injection flow rate), and the fault elasto-frictional and hydraulic properties. Unlike previous studies, our model accounts for the possibility that ruptures can propagate beyond the fluid-pressurized fault patch, a condition that is expected to occur in critically stressed and/or highly-pressurized fractures/faults. We test the scaling relation against estimates of moment release due to aseismic motion during fluid injections that vary in size from laboratory experiments to industrial applications. Our predictions are in good agreement with these observations. These results provide a simple means to quantify the size of aseismic ruptures in response to fluid injections related to both natural and human sources.

# S25C-0243: A Scaling Relation Between the Moment Release due to Aseismic Motion and the Injected Volume of Fluid

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## 1. Motivation

Constraining the moment release associated with injection-induced fault slip is of first importance to assess the seismic hazard of subsurface fluid injections in the geo-energy industry. Experimental and observational studies suggest that a significant part of the moment release during injections may be due to aseismic motion. Current models of injection-induced aseismic moment do not incorporate fault rupture mechanics. Here, we derive a physics-based scaling relation between the aseismic moment $M_0$ and a key operational parameter, the injected volume of fluid $V$.

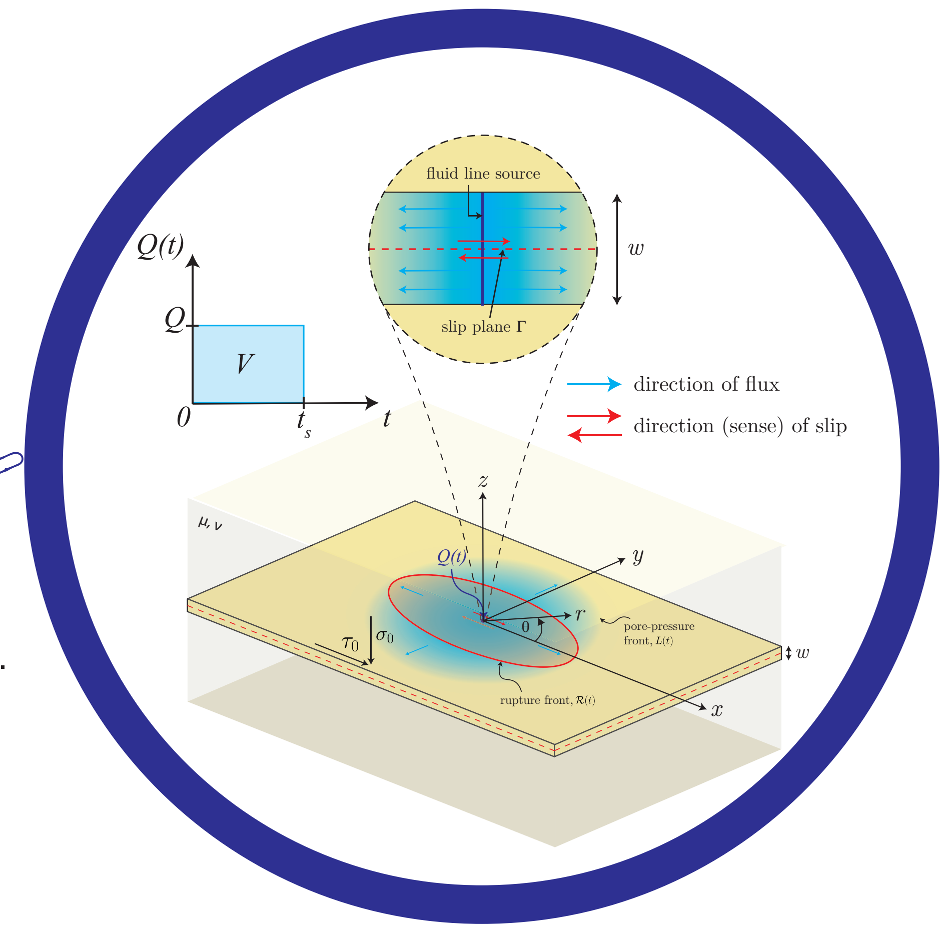
## 2. Model

We consider the nucleation, propagation and arrest of a quasi-static stable frictional shear crack (modes II+III) driven by a pulse of injection.

Our model has the following **assumptions**:

- Planar fault in an unbounded linearly elastic solid.
- Slip plane slides with a constant friction coefficient.
- Fault zone has a constant permeability and no leak-off.
- Line-fluid source at constant injection rate followed by shut-in.
- Uniform in-situ stress tensor and pore pressure field.

We solve the problem via a fully-implicit boundary-element-based method with elasto-plastic-like interfacial constitutive law.




## 3. Stress-injection parameter

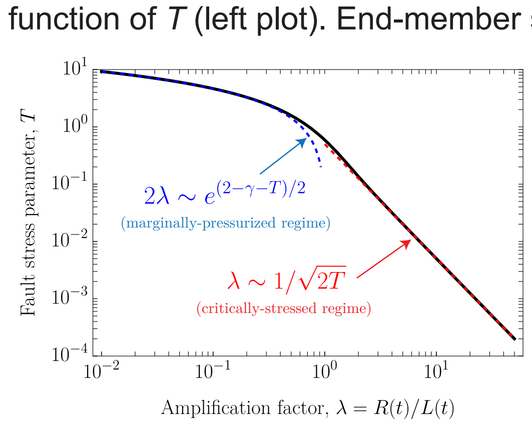
Our model is governed by essentially one non-dimensional parameter:

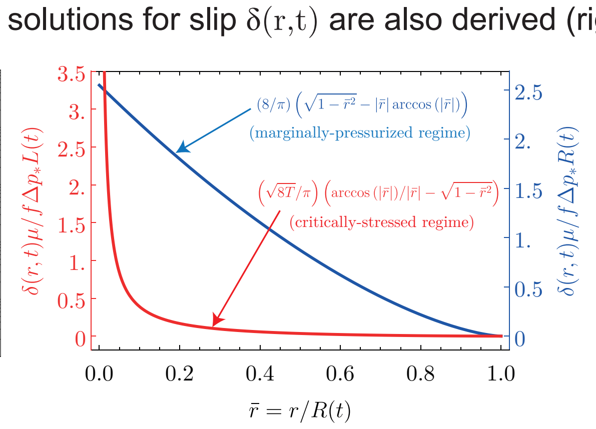
$$T = \frac{f\sigma'_0 - \tau_0}{f\Delta p_*} \text{, with } \Delta p_* = \frac{Q\eta}{4\pi k w}$$

where $f\sigma'_0 - \tau_0$ is the the "distance" to failure under ambient conditions (initial shear strength minus initial shear stress), and $f\Delta p_*$ is the strength of the injection, with $Q$ the injection rate, $\eta$ the fluid dynamic viscosity, and $kw$ the fault hydraulic transmissivity.

## 4. Solution before shut-in

Here, fault slip is self-similar (and diffusive). The rupture radius evolves as $R(t) = \lambda L(t)$ where $L(t) = \sqrt{4\alpha t}$ is the nominal position of the pore-pressure front (with $\alpha$ the fault hydraulic diffusivity) and $\lambda$ is the so-called amplification factor, known analytically as function of $T$ (left plot). End-member solutions for slip $\delta(r,t)$ are also derived (right plot).




## Main Findings:

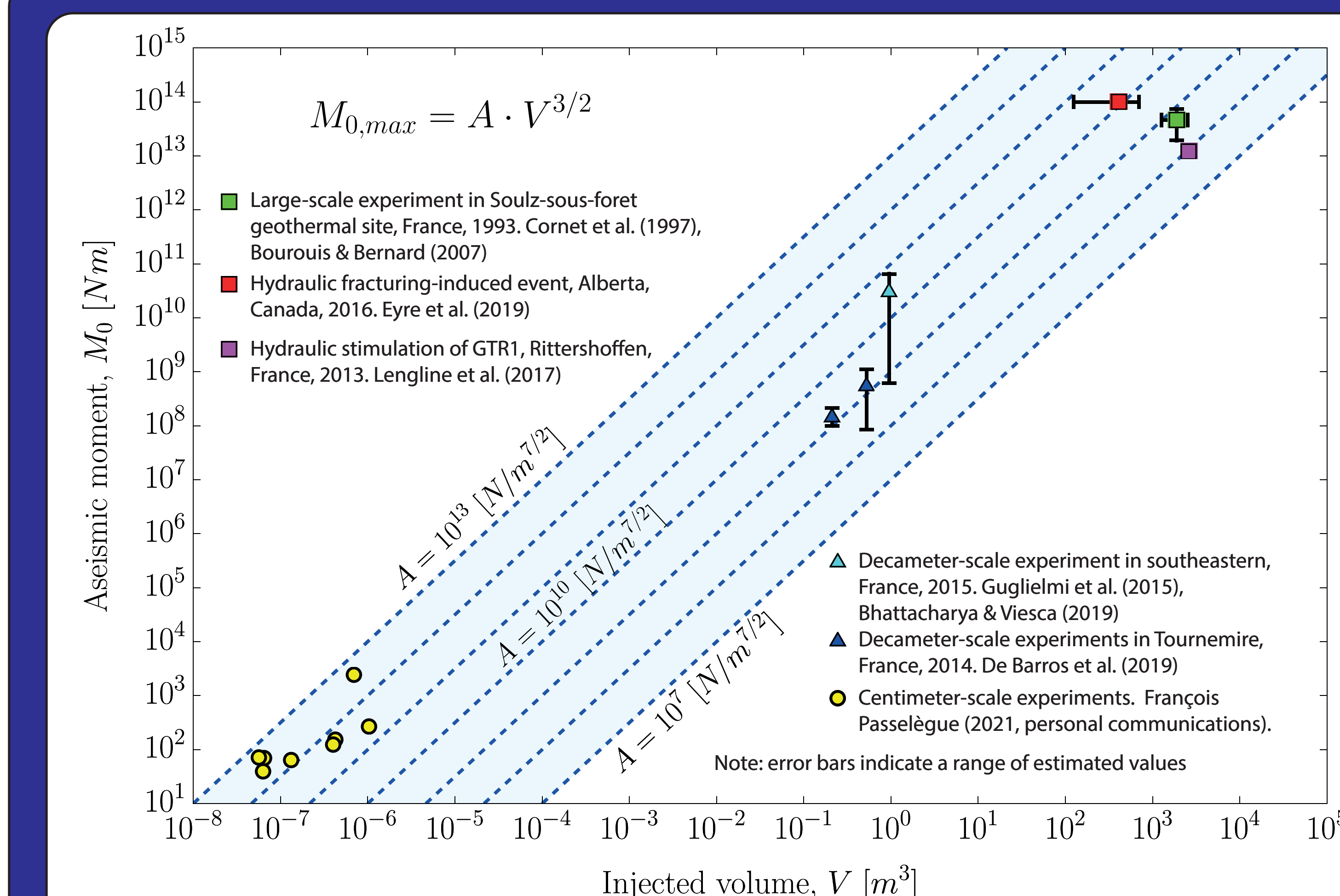
- Physics-based estimate of the radius at arrest of injection-induced aseismic ruptures.
- Upper bound for the aseismic moment:

$$M_{0,max} = A \cdot V^{3/2}$$

the pre-factor $A$ depends mainly on the pre-injection stress state and fault hydraulic properties.

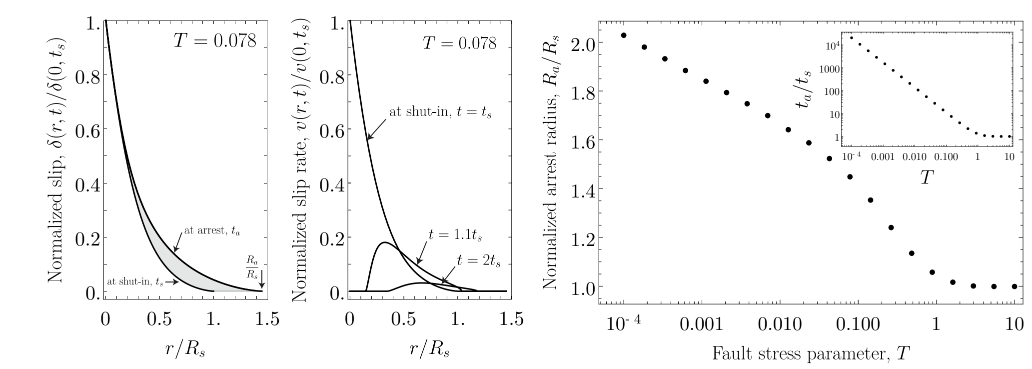
- Predictions are in good agreement with estimates of fluid injections from laboratory experiments to industrial applications.

## Comparison to fluid injection cases



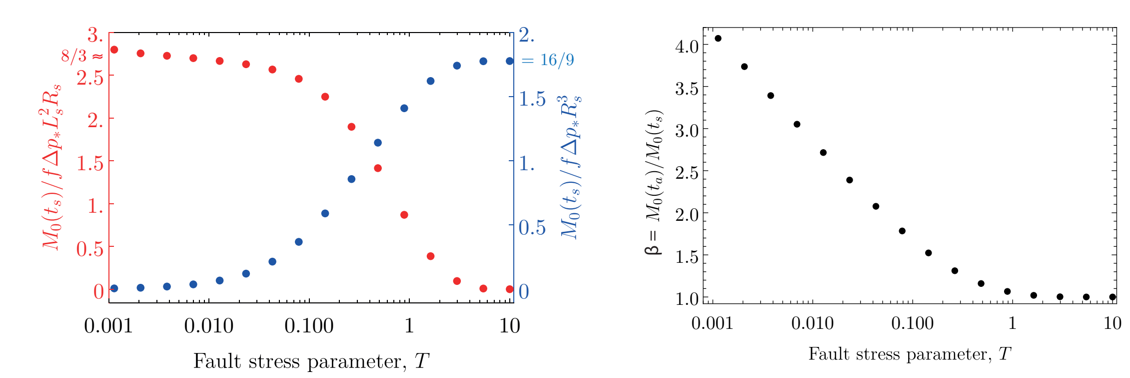

## 5. Solution after shut-in

After shut-in, self-similarity is broken. Moreover, fault slip undergoes a transition from crack-like to pulse-like rupture (left plots). The more critically stressed the fault is, the further the rupture propagates before arresting. We determine the arrest time $t_a$ and the arrest radius of the rupture $R_a$, as function of the fault stress parameter $T$ (right plot).




## 6. Aseismic moment

At the shut-in time, the moment release is calculated analytically for the limiting cases of critically-stressed ($T$ small) and marginally-pressurized faults ($T$ large), and numerically for intermediate cases (left plot). The contribution of the shut-in stage to the aseimic moment is computed numerically as function of $T$ (right plot).




## 7. Pre-factor A

The pre-factor $A$ is given by: $A = \frac{\beta\,(f\alpha\eta/kw)^{3/2}}{(f\sigma'_0 - \tau_0)^{1/2}}$

where $f$ is the constant friction coefficient, $\alpha$ is the fault hydraulic diffusivity, $\eta$ is the fluid dynamic viscosity, $kw$ is the fault hydraulic transmissivity, $\sigma'_0$ is the initial effective normal stress, $\tau_0$ is the initial shear, and $\beta$ is a factor of order one that quantifies the contribution of the shut-in stage (right plot, previous section).

## References

Sáez, A., Lecampion, B., Bhattacharya, P., Viesca, R.C. (2021), Three-dimensional fluid-driven stable frictional ruptures. Manuscript submitted for publication.

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